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# SIMULTANEOUS HEAT AND MASS TRANSFER IN AGITATED DRYER

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***Abstract:***
Drum dryers are often used for moisture reduction of granulated material and wet sludge from municipal or industry waste water. Moisture reduction and thermal treatment can be done in agitated drum dryers where convective heat transfer is helped by contact heating jacket and sometimes by heated agitators as well.
For the description of simultaneous heat and mass transfer in the dryer, mathematical model was created to investigate the influence of the operating parameters. The model contains volumetric heat and mass transfer coefficients that are functions of contacting wet material and heated surface, contacting wet material and hot air, and contacting air and heated surface.
Measurement and evaluation methods have been developed for determining the volumetric heat and mass transfer coefficients of granulated materials. Relations between the volumetric transfer coefficients were determined, with dimensionless Nu'-Re' numbers. The mathematical model and the transfer coefficients make possible to calculate the main drum dryer parameters.

***Keywords:*** *direct-indirect dryer, agitated dryer, heat and mass transfer*.

## 1. INTRODUCTION

Drum drying is currently used in the chemical and process industries to dry heavy pastes, thick liquids and particulate solids. The mixing of the material to ensure a better heat transfer can be realized with rotating drum or with agitator.

For the investigation the drying process of wet granular solid an agitated direct (drying gas), indirect (heating wall) heated dryer was constructed.

Heat is also transferred to the material from the drying gas and the covered wall surface via convection and conduction. However, in applications involving relatively low temperatures (gas and wall temperature of approximate 100 °C), the wall-to-material and the drying gas-to-material heat transfer becomes the dominant mechanism *[2]*. So the effect of wall-to-drying gas heat transfer is negligible.

In a work Ding et al. *[3]* compared the empirical expressed Nusselt number (at the drying gas-material) with experimental results of Tscheng and Watkinson *[4]*. The difference between the plotted curves is significant, especially at low Reynolds numbers.

Ohmori et al. studied the effect of the clearance between heating wall and agitated material to the heat transfer *[5]*. In our research this effect was neglected.

**2. MATHEMATICAL MODELL**

For modelling the process of simultaneous heat and mass transfer in agitated dryer *[1]* described a method that takes into consideration the heat transmitted from the gas as well over the wall to the material to be dried. *Fig. 1.* shows the modes of heat transfer in a short section of the dryer.

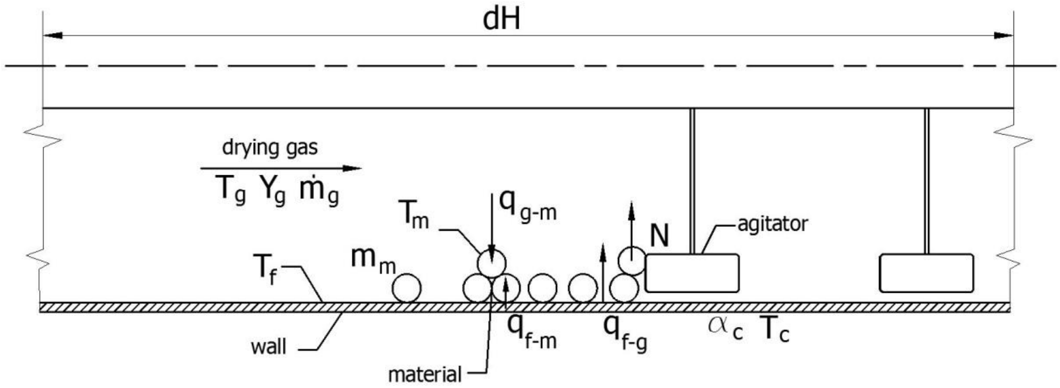


**Fig. 1.** Heat transfer in short section of the agitated dryer

With heat and mass balance for the differential section *dH*, the temperature and humidity of the drying gas and material can be deduced.

The variation of gas humidity along the length of the drum:

$$\frac{dY_g}{dH} = \frac{\sigma a_{g-m} A_q}{\dot{m}_g} (Y_F - Y_g) \tag{1}$$

The variation of the gas temperature along the length of the drum:

$$-\frac{dT_g}{dH} = \frac{A_q}{\dot{m}_g c_g} \left[ \alpha_{g-m} a_{g-m} (T_g - T_m) - k_{cv} a_{f-g} (T_c - T_g) \right] + \frac{c_{pWG}}{c_g} \frac{dY_g}{dH} (T_g - T_F) \tag{2}$$

The variation of the moisture content of the drying material along the drum length:

$$-\frac{dX}{dH} = \frac{\dot{m}_g}{\dot{m}_m} \frac{dY_g}{dH} \tag{3}$$

The variation of the temperature of the drying material along the drum length:

$$\frac{dT_m}{dH} = \frac{A_q}{\dot{m}_m c_m} \left[ k_{ct} a_{f-m} (T_c - T_m) + \alpha_{g-m} a_{g-m} (T_g - T_m) \right] + \frac{r_F}{c_m} \frac{dX}{dH} \tag{4}$$

Transfer coefficients in *Eq. (1) – (4)*

- from the heat flow between the gas and the material:

$$dQ_{g-m} = \alpha_{g-m} (T_g - T_m) dA_{g-m} \tag{5}$$

- from the heat flow between the wall and the gas:

$$dQ_{f-g} = k_{cv} (T_c - T_g) dA_{f-g} \tag{6}$$

- from the heat flow between the wall and the material:

$$dQ_{f-m} = k_{ct} (T_c - T_m) dA_{f-m} \tag{7}$$

- from Lewis analogy:

$$\frac{\alpha_{g-m}}{\sigma_{g-m}} = c_g Le^z \tag{8}$$

for the system air-water vapour:

$$Le^z \approx 1 \tag{9}$$

Volumetric contact area
- between the gas and the material:

$$a_{g-m} = \frac{dA_{g-m}}{A_q dH} \tag{10}$$

- between the wall and the gas:

$$a_{f-g} = \frac{dA_{f-g}}{A_q dH} \tag{11}$$

- between the wall and the material:

$$a_{f-m} = \frac{dA_{f-m}}{A_q dH} \tag{12}$$

Overall convective heat transfer coefficient between the wall and the gas:

$$\frac{1}{k_{cv} a_{f-g}} = \frac{1}{\alpha_{f-g} a_{f-g}} + \frac{1}{\alpha_c a_{f-g}} + \Sigma R_{f-g} \tag{13}$$

in those case $\alpha_{f-g} << \alpha_c$ can be calculated approximately $k_{cv} a_{f-g} \cong \alpha_{f-g} a_{f-g}$.

Overall contact heat transfer coefficient between the wall and the material:

$$\frac{1}{k_{ct} a_{f-m}} = \frac{1}{\alpha_{f-m} a_{f-m}} + \frac{1}{\alpha_c a_{f-m}} + \Sigma R_{f-m} \tag{14}$$

in those case $\alpha_{f-m} << \alpha_c$ can be calculated as $k_{ct} a_{f-m} \cong \alpha_{f-m} a_{f-m}$.

For the calculation the drum length by *Eq. (1)-(4)* volumetric heat and mass transfer coefficients $\alpha_{g-m} a_{g-m}$; $\alpha_{f-g} a_{f-g}$; $\alpha_{f-m} a_{f-m}$; $\sigma_{g-m} a_{g-m}$ are required.

## 3. DETERMINATION OF THE VOLUMETRIC HEAT AND MASS TRANSFER COEFFICIENTS

### *3.1. Measurement description*

The drying experiments were conducted in a pilot plant unit shown in *Figure 2*. On this scheme all measured and control variables are indicated with instrument symbols. The instrumentation of the pilot plant dryer are built up by standard sensors.
Central part of the mechanical system is a drum dryer (1). It is an 850 mm long agitated batch dryer consisting of a 250 mm wide U-form drying space covered by a flat plate. The feed (pasty or granular material) is agitated by an electrically driven scraping-agitator set (2). The agitator speed is adjustable by the aid of a variable frequency drive (SIC-10). Drying gas is fed axially at one end and let out at other end at the top. The construction of the dryer makes it possible to carry out experiments either with conductive or convective heating or applying both. On the cylindrical bottom part of the drying space a controlled electric heater (TIC-6) is built on.

The drying drum, the electric engine and the gearbox driving the agitator are built on a frame that is hung on a well-constructed weighing system with load cell (WI-11). Capacitive humidity sensors are used for relative humidity measurement (XI-3, 8). Differential pressure transmitter is used by measurement of gas flow. The pressure difference before and after the orifice plate is used to calculate the flow velocity (FI-2). Thermocouples (TI-4, 7, 9) and an infrared sensor (TI-5) are used for temperature measurement.

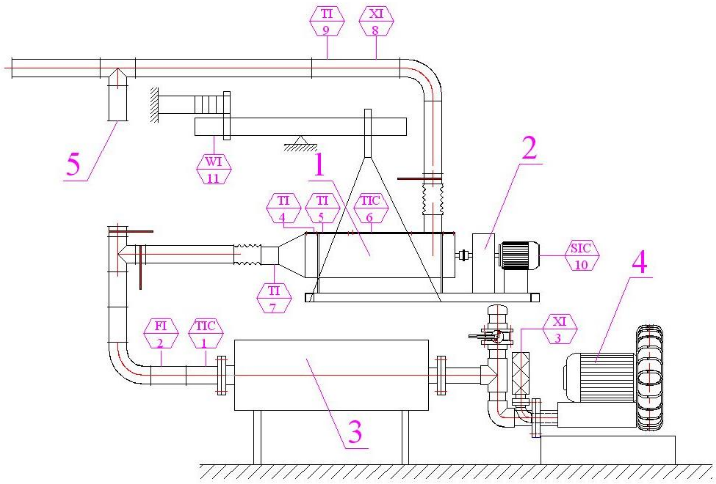


**Fig. 2.** Pilot-plant agitated drum dryer equipment

Drying air is heated by electric heater (3). The temperature of the drying air is controlled with temperature control (TIC-1). The volumetric flow rate of drying gas is varied by a variable frequency driven blower (4). At the start of the experiments, the dryer was set to the required drying conditions, i.e., the temperature, humidity and velocity of the inlet drying air were constant. The measured temperatures, humidity, mass and velocity were recorded in every minute by using a data logger.
The position and the main measures of the agitator and the cross-section of drum dryer can be seen in the *Figure 3*.

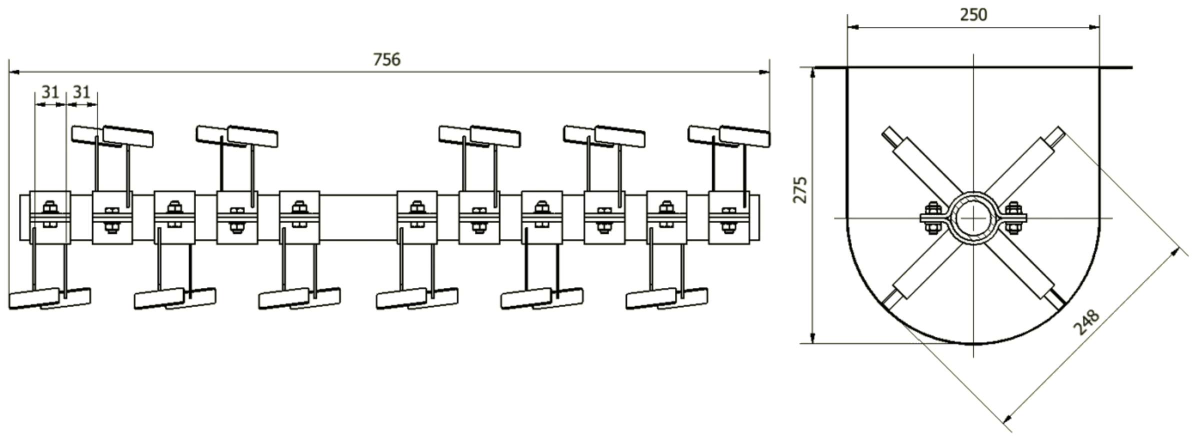


**Fig. 3.** The agitator

### *3.2. Evaluation method*

In agitated dryer the contacting surfaces for heat transfer both from the gas side and heated wall side cannot be measured exactly. For this case the volumetric heat transfer coefficients are defined.

For the evaluation of the heat and mass transfer coefficient between the gas and the material the drying process was carried out only with hot air. In the constant drying rate period the heat transferred from the gas to the material is consumed by evaporation:

$$\alpha_{g-m}(T_g - T_m)A_{g-m} = N_{const} r A_{g-m} = r\,\sigma_{g-m}(Y_{surface} - Y_g)A_{g-m} \tag{15}$$

Drying rate in the constant drying period:

$$N_{const} = \frac{\Delta m_m}{A_{g-m} \cdot \Delta t} = \sigma_{g-m}(Y_{surface} - Y_g) \tag{16}$$

According to *Eq. (10)*

$$A_{g-m} = a_{g-m} A_q H = a_{g-m} V \tag{17}$$

From *Eq. (15)-(17)* the volumetric heat transfer coefficient between the gas and the material for the constant drying rate period, where $T_m$=constant:

$$\alpha_{g-m} \cdot a_{g-m} = \frac{\Delta m_m}{\Delta t} \frac{r}{\Delta T_{\log} V} \tag{18}$$

Similarly to the previous case, for the constant drying rate period when heat is transferred only from the wall toward the material the volumetric heat transfer coefficient between the wall and the material:

$$\alpha_{f-m} \cdot a_{f-m} = \frac{\Delta m \cdot r}{\Delta t (T_f - T_m) V} \tag{19}$$

### *3.3. Results of the measurement*

**Table 1.** Measured and evaluated quantities

| Material | $d$ | $T_f$ | $T_{g,in}$ | $n$ | $l$ | $\dot{V}_g$ | $\alpha_{g-m} \cdot a_{g-m}$ | $\alpha_{f-m} \cdot a_{f-m}$ | |
|---|---|---|---|---|---|---|---|---|---|
| | [m] | [°C] | [°C] | [1/s] | [1] | [m³/s] | [W/m³K] | [W/m³K] | |
| maize | 0,0060 | no | 100 | 0,633 | 0,2277 | 0,00269 | 219,7 | | DRYING GAS (direct) |
| maize | 0,0060 | no | 100 | 0,950 | 0,2277 | 0,00250 | 238,7 | | |
| maize | 0,0060 | no | 100 | 1,267 | 0,2192 | 0,00259 | 334,6 | | |
| teamarc | 0,0010 | no | 90 | 0,475 | 0,2530 | 0,02858 | 343,0 | | |
| teamarc | 0,0010 | no | 93 | 0,475 | 0,2530 | 0,03350 | 359,0 | | |
| teamarc | 0,0010 | no | 81 | 0,475 | 0,2530 | 0,03339 | 287,0 | | |
| millet | 0,0015 | no | 100 | 0,633 | 0,1605 | 0,05484 | 139,5 | | |
| millet | 0,0015 | no | 100 | 0,333 | 0,1300 | 0,05484 | 120,9 | | |
| millet | 0,0015 | no | 100 | 0,500 | 0,1300 | 0,05484 | 151,8 | | |
| millet | 0,0015 | no | 100 | 0,667 | 0,1300 | 0,05484 | 183,6 | | |
| millet | 0,0015 | no | 100 | 0,833 | 0,1300 | 0,05484 | 246,8 | | |
| millet | 0,0015 | no | 100 | 1,000 | 0,1300 | 0,05484 | 407,7 | | |
| millet | 0,0015 | no | 100 | 0,333 | 0,2000 | 0,05484 | 153,1 | | |
| millet | 0,0015 | no | 100 | 0,500 | 0,2000 | 0,05484 | 178,0 | | |
| millet | 0,0015 | no | 100 | 0,667 | 0,2000 | 0,05484 | 242,4 | | |
| millet | 0,0015 | no | 100 | 0,833 | 0,2000 | 0,05484 | 289,7 | | |
| millet | 0,0015 | no | 100 | 1,000 | 0,2000 | 0,05484 | 477,7 | | |
| millet | 0,0015 | no | 100 | 0,500 | 0,2500 | 0,05484 | 214,3 | | |
| millet | 0,0015 | no | 100 | 0,667 | 0,2500 | 0,05484 | 281,2 | | |
| millet | 0,0015 | no | 100 | 0,833 | 0,2500 | 0,05484 | 352,8 | | |
| millet | 0,0015 | no | 100 | 1,000 | 0,2500 | 0,05484 | 495,4 | | |
| maize | 0,0060 | 90 | 100 | 0,950 | 0,2382 | 0,00261 | 674,3 | 819,1 | DRYING GAS + HEATING WALL (direct+indirect) |
| maize | 0,0060 | 88 | 100 | 1,267 | 0,2382 | 0,00257 | 962,4 | 1163,9 | |
| maize | 0,0060 | 50 | 85 | 0,633 | 0,1726 | 0,00260 | 132,1 | 882,3 | |
| millet | 0,0015 | 50 | 85 | 0,633 | 0,1605 | 0,05500 | 167,5 | 1238,7 | |
| corngris | 0,0010 | 70 | 98 | 0,633 | 0,2256 | 0,05200 | 466,4 | 1450,0 | |
| corngris | 0,0010 | 80 | 98 | 0,633 | 0,2256 | 0,05250 | 532,1 | 1300,0 | |
| corngris | 0,0010 | 90 | 98 | 0,633 | 0,2256 | 0,05200 | 582,0 | 1270,0 | |

### *3.4. Correlations with dimensionless numbers*

From the volumetric heat transfer coefficient a modified Nu'-number was created, both for the gas-material and wall-material heat transfer:

$$Nu'_{g-m} = \frac{(\alpha \cdot a)_{g-m} \cdot d^2}{\lambda_g} \qquad Nu'_{f-m} = \frac{(\alpha \cdot a)_{f-m} \cdot d^2}{\lambda_m} \qquad (20)\text{-}(21)$$

Suppose that a particle is rotating and moving along the drum length. The average velocity from the respectively particle and gas velocities vector:

$$w = \sqrt{w_{cir}^{\;2} + w_{ax}^{\;2}} \qquad (22)$$

The modified Reynolds-number with the circumferential and the axial velocities:

$$Re' = \frac{w \cdot d}{\nu_g} \qquad (23)$$

The drum loading factor:

$$l = \frac{V_m}{V_d} == \frac{V_m}{A_q H} \qquad (24)$$

From the experiments listed above in *Table 1.* the modified $Nu'_{g\text{-}m}$–$Re'$ correlation are illustrated in *Fig. 4.* for convective heat transfer between the gas and the drying material. *Fig. 5.* shows the correlation between $Nu'_{f\text{-}m}$ –$Re'$ for contact heat transfer between the wall and the drying material.
The results in *Fig. 4.* and *Fig. 5.* are valid in the intervals:

$$25{,}9 < Re' < 243$$
$$0{,}13 < l < 0{,}253$$

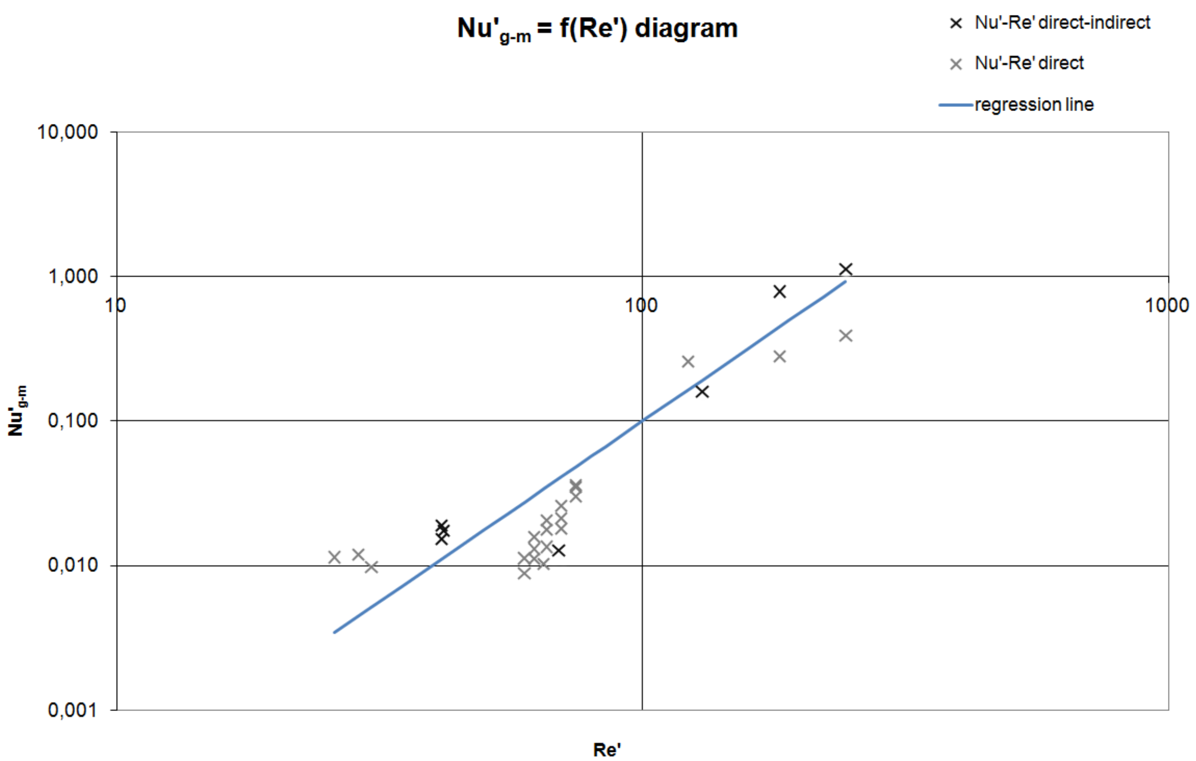


**Fig. 4.** Modified Nusselt and Reynolds number between the drying gas and the material

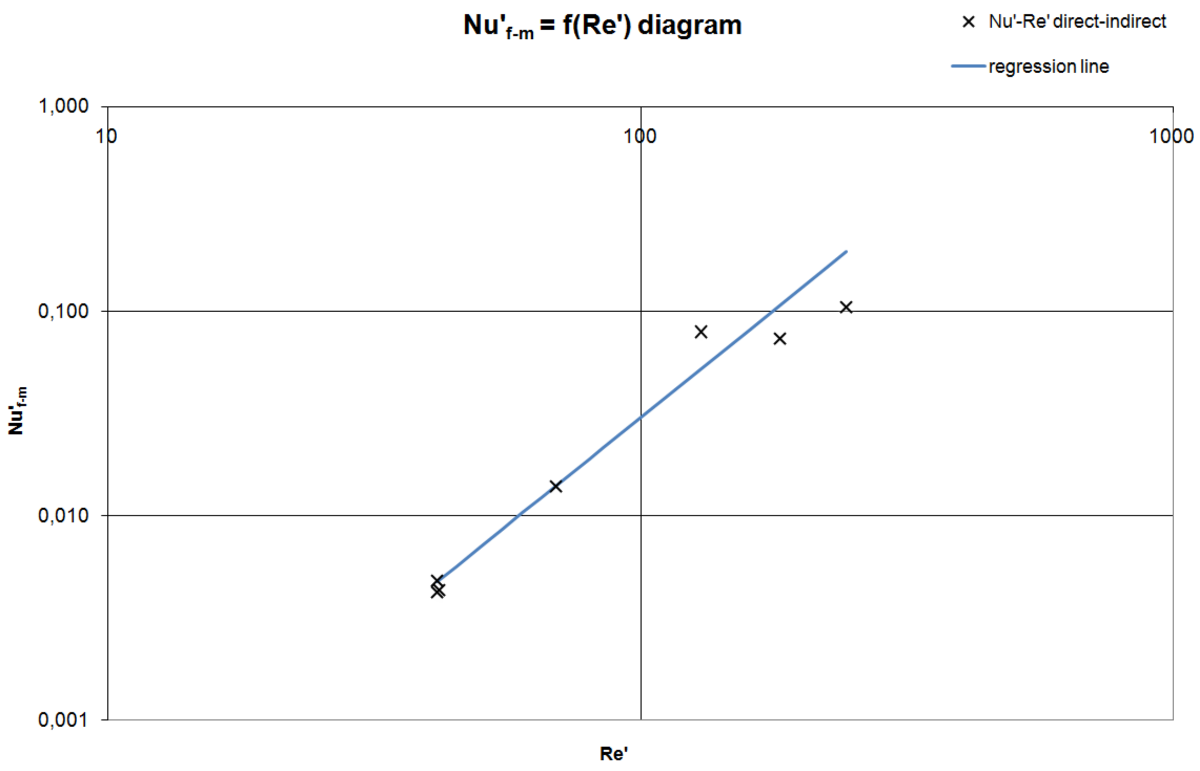


**Fig. 5.** Modified Nusselt and Reynolds number between the heated wall and the material

## 4. CONCLUSION

Measurements were carried out with different test materials (maize, millet, teamarc and corngris). The moisture content of the materials varied from the free surface moisture content near to the equilibrium moisture content. With the heat and mass balance of the dryer, and from the mass reduction of the material on the constant drying rate period the transfer coefficients can be determined. The heat and mass transfer coefficients serve as input parameter for the mathematical model. Relations between the dimensionless *Nu'-Re'* numbers for air-material and wall-material are demonstrated. Experiments will continue to determine exact equations between *Nu'–Re'* relation.

## 5. NOMENCLATURE

| *Roman letters* | | | *Greek letters* | | |
|---|---|---|---|---|---|
| Symbols | Denomination | Units | Symbols | Denomination | Units |
| $a$ | volumetric surface area | $m^2/m^3$ | $\alpha$ | heat transfer coefficient | $W/m^2K$ |
| $A$ | heat transfer area | $m^2$ | $\lambda$ | thermal conductivity | $W/mK$ |
| $A_q$ | cross sectional area | $m^2$ | $\sigma$ | mass transfer coefficient | $kg/m^2s$ |
| $c$ | specific heat | J/kgK | $\nu$ | kinematic viscosity | $m^2/s$ |
| $d$ | diameter of particle | m | | | |
| $H$ | length of drum dryer | m | | *Subscripts* | |
| $k$ | overall heat transfer coefficient | $W/m^2K$ | Symbols | Denomination | |
| $l$ | drum loading factor | 1 | $'$ | modified | |
| $Le$ | Lewis number | 1 | $ax$ | axial | |
| $m$ | mass | kg | $c$ | condense | |
| $\dot{m}$ | mass flow | kg/s | $cir$ | circumferential | |
| $n$ | rotation | 1/s | $ct$ | contact | |
| $N$ | drying rate | $kg/m^2s$ | $cv$ | convective | |
| $Nu$ | Nusselt number | 1 | $d$ | drum | |
| $q$ | heat flux | $W/m^2$ | $f$ | inner surface of the drum | |
| $r$ | heat of evaporation | J/kg | $F$ | surface | |
| $R$ | resistance | $m^3K/W$ | $f\text{-}m$ | wall – material | |
| $Re$ | Reynolds number | 1 | $f\text{-}g$ | wall – drying gas | |
| $t$ | time | s | $g$ | drying gas | |
| $T$ | temperature | °C | $g\text{-}m$ | drying gas - material | |
| $\dot{V}$ | flow rate | $m^3/s$ | $in$ | inlet | |
| $V$ | volume | $m^3$ | $m$ | material | |
| $w$ | air velocity | m/s | $v$ | vapour | |
| $X$ | moisture content of the material | kg/kg | $WG$ | water vapour | |
| $Y$ | absolute humidity of the gas | kg/kg | $z$ | constant | |

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